

SIMULATION OF METHANE EMISSIONS FROM DAIRY FARMS TO ASSESS GREENHOUSE GAS REDUCTION STRATEGIES

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ABSTRACT. As a sector, agriculture is reported to be the second greatest contributor to atmospheric methane (CH_4) in the U.S., emitting 31% of the total emission. Primary sources of CH_4 on dairy farms are the animals and manure storage, with smaller contributions from field-applied manure, feces deposited by grazing animals, and manure on barn floors. The Integrated Farm System Model (IFSM) was expanded to include simulation of CH_4 emissions from all farm sources along with modules predicting other greenhouse gas (GHG) emissions. The new CH_4 module incorporated previously published relationships and experimental data that were consistent with our modeling objectives and the current structure of IFSM. When used to simulate previously reported experiments, the model was found to predict enteric fermentation and slurry manure storage emissions similar to those measured. In simulating a representative 100-cow dairy farm in Pennsylvania, the model predicted a total average annual emission of 21 Mg CH_4 . This included annual emissions of 142 kg CH_4 per cow from the Holstein herd and 6.4 kg CH_4 per m^3 of slurry manure in storage, which were consistent with previously summarized emission data. To illustrate the use of the expanded whole-farm model, potential CH_4 reduction strategies were evaluated. Farm simulations showed that increasing the production and use of forage (corn silage) in animal diets increased CH_4 emission by 16% with little impact on the global warming potential of the net farm emission of all GHGs. Use of grazing along with high forage diets reduced net farm GHG emission by 16%. Using an enclosed manure storage and burning the captured biogas reduced farm emission of CH_4 by 32% with a 24% reduction in the net farm emission of GHG. Incorporation of GHG emission modules in IFSM provides a tool for estimating whole-farm emissions of CH_4 and evaluating proposed reduction strategies along with their impact on net GHG emission and other environmental and economic measures.

Keywords. Dairy farm, Greenhouse gas, Methane, Simulation model.

The Intergovernmental Panel on Climate Change (IPCC) has reported that it is “extremely likely” (representing a 95% confidence level or higher) that anthropogenic emissions of greenhouse gases (GHGs) are causing a change in the global climate (IPCC, 2007). Although many mitigation plans currently focus on reducing carbon dioxide (CO_2) emissions, methane (CH_4) is a stronger GHG, with a global warming potential about 25 times that of CO_2 (IPCC, 2007). The Food and Agriculture Organization of the United Nations (FAO, 2006) has claimed that livestock emit 37% of anthropogenic CH_4 on a global basis. In 2007, agriculture was reported to be the second greatest contributor of total CH_4 emission in the U.S. with 31%, behind only the energy sector (41%) and a little greater than human waste management (28%) in overall impact (EIA, 2007). Therefore, quantifying and reducing CH_4 emissions

from livestock farms is important for developing more sustainable production systems.

Multiple processes emit CH_4 from dairy farms, including enteric fermentation in animals and microbial processes in manure. A review of agricultural emission data shows that the majority of CH_4 from dairy farms is created through enteric fermentation, followed by emissions from manure storages (Chianese et al., 2009c). In addition to these major sources, smaller emissions result from field-applied manure and manure deposited by animals inside barns or on pasture. Recent research has shown that plants may also emit CH_4 , although the mechanism is not currently known (Keppler and Röckmann, 2007). Most field studies (e.g., Sherlock et al., 2002), as well as our review of agricultural emissions (Chianese et al., 2009c), report croplands as a negligible source, or small sink, of CH_4 over full production years. However, field-applied manure can result in significant emissions for a few days after application (Chadwick and Pain, 1997; Sherlock et al., 2002).

Computer simulation provides a cost-effective and efficient method of estimating CH_4 emissions from dairy farms and analyzing how management scenarios affect these emissions. The Integrated Farm System Model (IFSM; USDA-ARS, University Park, Pa.) is a process-based, whole-farm simulation including major components for soil processes, crop growth, tillage, planting and harvest operations, feed storage, feeding, herd production, manure storage, and economics (Rotz et al., 2009). IFSM predicts the effect of management scenarios on farm performance, profitability, and

Submitted for review in July 2008 as manuscript number SE 7621; approved for publication by the Structures & Environment Division of ASABE in July 2009. Presented at the 2008 ASABE Annual Meeting as Paper No. 084098.

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environmental pollutants such as nitrate leaching, ammonia volatilization, and phosphorus runoff loss.

Our goal was to develop a tool for estimating GHG emissions from dairy farms and quantifying management effects on emissions. To accomplish this, modules were incorporated in IFSM to simulate processes controlling CH₄ emissions. Specific objectives were to review published models for simulating CH₄ emissions, identify relationships that best fit our modeling goals, adapt those models for use in IFSM, verify that the models gave reasonable predictions, and demonstrate the use of this tool in predicting whole-farm CH₄ emissions and the impact of reduction strategies. The CH₄ module was developed along with modules simulating CO₂ (Chianese et al., 2009a) and nitrous oxide (N₂O, Chianese et al., 2009b) emissions to predict net farm emission of GHG.

MODEL DEVELOPMENT

The Integrated Farm System Model is a simulation model that integrates the major biological and physical processes of a crop, beef, or dairy farm (Rotz et al., 2009). Crop production, feed use, and the return of manure nutrients back to the land are simulated over each of 25 years of weather. Growth and development of alfalfa, grass, corn, soybean, and small grain crops are predicted based on daily soil and weather conditions. Tillage, planting, harvest, storage, and feeding operations are simulated to predict resource use, timeliness of operations, crop losses, and nutritive changes in feeds. Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of the animal groups making up the herd. The quantity and nutrient content of the manure produced is a function of the quantity and nutrient content of the feed consumed. Nutrient flows through the farm are modeled to predict nutrient accumulation in the soil and loss to the environment. Environmental impacts include nitrogen (N) volatilization from manure sources, soil denitrification and leaching losses, erosion of sediment, and sediment-bound and soluble phosphorus (P) losses in runoff. Whole-farm mass balances of N, P, and potassium are determined as the sum of all nutrient imports in feed, fertilizer, deposition, and legume fixation minus the exports in milk, excess feed, animals, manure, and losses leaving the farm. Simulated performance is then used to determine production costs, incomes, and economic return for the farm production system.

To include CH₄ emissions in IFSM, relationships were needed to predict the emission from each important farm source. Enteric fermentation and manure (primarily manure storages) are the major sources of CH₄ from farms, contributing about 65% and 30% of total agricultural CH₄ emission, respectively (EIA, 2007). Even though manure applied on fields, feces deposited on pasture, and manure on barn floors do not contribute large amounts of CH₄, relationships were included for these sources to obtain a comprehensive prediction of farm-level emissions. A number of models have been published that predict emissions from the major sources. To create our module, we selected relationships that best fit our needs for whole-farm simulation. Criteria used to evaluate potential models were:

1. The model had to be capable of simulating important processes that affect CH₄ emissions with changes in farm management. Strategies to reduce CH₄ emissions from en-

teric fermentation primarily involve animal diet. Strategies to reduce CH₄ emissions from manure storages include storage covers and capturing and burning the gas. In order to analyze how these and other practices affect CH₄ emissions, the model had to account for the associated processes (e.g., animal ration, manure type, and storage design).

2. The model had to provide process-level representation of major emission components. Several published models, as well as sections of the IPCC methodology, predict CH₄ emissions from farms using emission factors (e.g., Schils et al., 2005; Lovett et al., 2006). While these models are useful as simple tools for estimating CH₄ emissions, they do not have the capability of representing processes that affect CH₄ emissions. For example, Schils et al. (2005) simulated CH₄ emissions due to enteric fermentation in heifers and calves by multiplying a group-specific emission factor by the number of animals in each group. This model only accounted for the effect of animal numbers and would not account for diet modifications. Our goal was to select physically and biologically based relationships that also satisfied criterion 1.

3. The model had to satisfactorily predict observed data over a full range of potential conditions. The chosen relationships had to satisfactorily predict CH₄ emissions within the range of observed emissions from the given farm component over the full range of possible farm characteristics.

4. The model had to be consistent with the current scale of other components in IFSM. IFSM is designed to simulate realistic scenarios implemented on farms. Characteristics of these scenarios are designated at the farm management level (e.g., available feeds, sequence of machinery operations, manure storage duration). Subsequently, IFSM simulates processes, normally on a daily time step, at the field or farm level according to the assumed farm characteristics. As a result, selected relationships and their associated inputs and parameters had to function well at the field or farm level as opposed to other scales (e.g., microbiological or regional).

5. Model inputs and parameters were limited to readily available data. Some available mechanistic models accurately predict emissions; however, these models typically require many inputs and parameters. The required values are often the result of calibration against observed data, are difficult to obtain, or have no physical or biological basis. The uncertainty added by assuming these parameter values can outweigh the benefit of using a highly mechanistic model. In contrast, the majority of parameters and inputs in IFSM are easily obtained through on-farm observation. Thus, our final criterion was that input and parameter values were easily obtained within, or consistent with, the current structure of IFSM.

For the relatively minor emission sources of manure on the barn floor and feces of grazing animals, published models were not available. In these cases, simpler models or emission factors were used. This simpler approach was justified given their lesser importance in contributing to whole-farm emissions.

ENTERIC FERMENTATION

Ruminant animals subsist primarily on forages. Like most animals, ruminants do not have the enzymes necessary to break down cellulose. However, bacteria in the rumen break down and obtain energy from cellulose in the forage con-

sumed by the animal, producing hydrogen as one by-product. If the produced hydrogen is allowed to build up in the rumen, it can lead to acidosis, a health problem in dairy cows. However, enteric methanogens, which exist in a symbiotic relationship with other microorganisms in the rumen, prevent the build-up of hydrogen by using it to reduce CO₂ to CH₄, which is then released to the atmosphere by eructation and respiration. Other roles of these microorganisms are not fully understood (Madigan et al., 2003). The amount of CH₄ produced from enteric fermentation is influenced by various factors including animal type and size, digestibility of the feed, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (Monteny et al., 2001; Wilkerson et al., 1995).

A number of models have been published to predict the CH₄ produced by ruminant animals. The more mechanistic models (e.g., Baldwin et al., 1987; Dijkstra et al., 1992; Mills et al., 2001) simulate the chemical or microbiological processes occurring in the rumen that produce CH₄. These models are often highly detailed and require many state variables and equations. The more empirical models use equations relating CH₄ emissions to various factors such as feed intake (Blaxter and Clapperton, 1965), feed characteristics (Moe and Tyrrell, 1979), milk yield and live weight (Kirchgessner et al., 1991), dry matter intake and feed characteristics (Yates et al., 2000), and metabolizable energy intake and feed characteristics (Mills et al., 2003). These models range from equations based solely on statistical correlations to biological based relationships.

Reviews of both mechanistic and empirical models have been published (Wilkerson et al., 1995; Benchaar et al., 1998; Mills et al., 2003). Mechanistic models, such as that of Mills et al. (2001), have been shown to explain more variation as compared to empirical models. Relative to our model criteria, these models satisfied only criteria 1, 2, and 3. This microbiological approach required more detail than needed or desired for simulating processes at the whole-farm scale. More importantly, the inputs and parameters required were not readily available or easily set.

To best meet the needs of our farm model, a simpler approach was taken using the Mitscherlich 3 (Mits3) equation developed by Mills et al. (2003). Mits3 is a simple process model that satisfies all five criteria. The model is based on dietary composition and is capable of accounting for management practices that alter the animal's intake and diet. Mits3 is process-based, relating CH₄ emissions to dietary intake as well as animal type and size. When compared to data from the U.S., Mits3 yielded a regression slope of 0.89 with an intercept of 3.50 and a square root of the mean square prediction error (MSPE) of 34.1% (Mills et al., 2003). In addition, Mits3 predicts realistic emissions at the extremes of parameter ranges. Thus, an additional benefit of the nonlinearity of Mits3 is that the model predicts reasonable emissions when applied to conditions outside those for which it was originally developed.

The structure and data requirements of Mits3 were consistent with the scale needed for whole-farm simulation. Only three model inputs were required: starch content of the diet, acid detergent fiber (ADF) content of the diet, and metabolizable energy intake. These inputs were readily obtained from the feed and animal components of IFSM. Through these inputs, CH₄ production was directly related to diet and indirectly related to animal number, size, and type. This allowed prediction of changes in CH₄ production as affected by

changes in animal nutrition and management. A detailed description of the selected model can be found in Mills et al. (2003). A brief description is provided here to document the model, parameters used, and the integration with IFSM.

Emission of CH₄ is predicted as:

$$E_{CH_4,ent} = [E_{max} - E_{max} \cdot \exp(-c \cdot M_{EI})] \cdot F_{kgCH_4} \quad (1)$$

where $E_{CH_4,ent}$ is the emission due to enteric fermentation (kg CH₄ animal⁻¹ day⁻¹), E_{max} is the maximum possible emission (MJ CH₄ animal⁻¹ day⁻¹), c is a shape parameter determining how emissions change with increasing M_{EI} (dimensionless), M_{EI} is the metabolizable energy intake (MJ animal⁻¹ day⁻¹), and F_{kgCH_4} is the conversion of MJ to kg of CH₄ (0.018 kg CH₄ MJ⁻¹). From Mills et al. (2003), the maximum possible emission is defined as 45.98 MJ CH₄ animal⁻¹ day⁻¹. This maximum possible emission is constant for all animals; the effect of animal size and type is indirectly provided through the value of M_{EI} . The shape parameter, c , is calculated as:

$$c = -0.0011 \cdot \left[\frac{Starch}{ADF} \right] + 0.0045 \quad (2)$$

where *Starch* is the starch content, and *ADF* is the acid detergent fiber content of the diet. Equation 2 models the observed trend of increased CH₄ emission with high-fiber diets and decreased emission with high-starch diets.

To use the above equations, values were needed for the starch and ADF contents of diets and the metabolizable energy intake of each animal group making up the herd. IFSM determines the ration that each animal group is fed based on a representative animal's nutritional requirements and the available feeds (Rotz et al., 1999). This information includes the required energy content of the diet (MJ kg DM⁻¹), the total dry matter intake (kg DM day⁻¹ animal⁻¹), and the amount of each feed used. The first two parameters are used to calculate M_{EI} . The ADF contents of feeds used in IFSM are determined assuming a linear relationship with neutral detergent fiber (NDF) for each feed type (table 1). These relationships were developed using feed composition data from the National Research Council (NRC, 2001). The starch contents of feeds are determined assuming a linear relationship with the amount of nonfiber carbohydrate (NFC) in the feed (table 1). The fraction of NFC is determined as:

$$F_{NFC} = 1 - (F_{NDF} + F_{CP} + F_{fat} + F_{ash}) \quad (3)$$

where F_{NFC} is the fraction of NFC in the diet, F_{CP} is the fraction of crude protein (CP), F_{fat} is the fraction of fat, and F_{ash} is the fraction of ash in the diet. The fractions of NDF and CP were available in IFSM; typical fractions of fat and ash (table 1) were obtained from the National Research Council (NRC, 2001). A given animal group is typically fed a mixture of feeds making up the whole diet. A weighted average of the individual feed characteristics in the ration is used to determine the starch and ADF contents of the full ration fed to each of the six possible animal groups making up the herd (Rotz et al., 1999).

MANURE STORAGE

During manure storage, CH₄ is generated through a reaction similar to that described for enteric fermentation. The

Table 1. Relationships used to model starch and acid detergent fiber (ADF) contents of feeds in IFSM.^[a]

Feed Type	Starch (fraction)	ADF (fraction)
Alfalfa hay	0.64*(1- F_{NDF} - F_{CP} -0.11)	0.78* F_{NDF}
Alfalfa silage	0.89*(1- F_{NDF} - F_{CP} -0.12)	0.82* F_{NDF}
Grass hay	0.45*(1- F_{NDF} - F_{CP} -0.11)	0.61* F_{NDF}
Grass silage	0.65*(1- F_{NDF} - F_{CP} -0.12)	0.64* F_{NDF}
Corn grain	0.68	0.036
High-moisture corn	0.52	0.004
Corn silage	0.80*(1- F_{NDF} - F_{CP} -0.07)	0.62* F_{NDF}
Perennial grass/legume	0.48*(1- F_{NDF} - F_{CP} -0.14)	0.72* F_{NDF}
Alfalfa pasture	0.48*(1- F_{NDF} - F_{CP} -0.14)	0.55* F_{NDF}
Protein supplement 1	0.0	0.0
Protein supplement 2	0.0	0.0
Fat additive	0.0	0.0

^[a] F_{NDF} (fraction of neutral detergent fiber in feed) and F_{CP} (fraction of crude protein in feed) are available in IFSM. The last value in the equations developed to predict starch content represents an average total of fat plus ash contents for the given feed. Typical values for fat and ash were obtained from NRC (2001).

cellulose in the manure is degraded by microbes, with products of this process serving as substrates for methanogenesis. Temperature and storage time are the most important factors influencing CH₄ emissions from stored manure because substrate and microbial growth are generally not limited (Monteny et al., 2001). Although the processes are similar, the temperature in the storage varies, in contrast to the relatively constant temperature in the rumen, and the manure in storage is more heterogeneous (e.g., the substrate is less well mixed, and some carbohydrates are already partially decomposed) as compared to the consistency of the rumen (Monteny et al., 2001).

Both mechanistic and empirical models have been developed to predict CH₄ emissions from manure storages. Unlike some of the empirical enteric fermentation models that simply use statistical correlations, the majority of empirical manure storage models are biologically based. Two mechanistic models (Hill, 1982; García-Ochoa et al., 1999) and four empirical models (Chen and Hashimoto, 1980; Hill, 1991; Zeeman, 1994; Sommer et al., 2004) were considered for our application. Of all models found, these six represented those most appropriate for simulating manure storage emissions.

The more mechanistic models of Hill (1982) and García-Ochoa et al. (1999) satisfied criteria 1, 2, and 3 of our model requirements, but were less satisfactory for criteria 4 and 5. These models simulated CH₄ production based on the chemical and microbiological reactions in the storage. As a result, the model scale was not consistent with that of IFSM. Additionally, there were many model parameters that required iterative solutions or were difficult to obtain or set over the range of possible storage conditions.

Of the four empirical models considered, three were found to satisfy all five of our model criteria. The model of Hill (1991) was dropped because this model was developed for anaerobic digesters, and the empirical parameters were not verified to be applicable for manure storages with no treatment. From the remaining three models, the model of Sommer et al. (2004) was selected for our application. Their model employed commonly used empirical relationships (e.g., Arrhenius relationship) that were more general and thus more applicable to conditions outside of those for which they were developed. Additionally, this was a more recent model,

incorporating more recent developments and data. The model of Chen and Hashimoto (1980) was similar in design. Although it could be applied to fresh manure, this model was primarily developed to simulate anaerobic digesters, and several of the parameters were empirically determined based on data from digesters. Zeeman (1994) used biologically based equations to predict CH₄ production but used emission factors, or a similar method, to predict the actual emission of CH₄ from digested manure. Unlike the other models, the model of Sommer et al. (2004) was developed for more general application to either digested or raw slurry manure.

The model of Sommer et al. (2004) simulates the production and emission of CH₄ from manure storages based on the degradation of volatile solids (VS). Additional factors affecting CH₄ production are temperature and storage time. A detailed description of the development of the model is found in Sommer et al. (2004). The model is presented here along with a brief discussion on how the parameters were determined and how the model was integrated with IFSM.

Emission of CH₄ from manure storage is predicted as:

$$E_{CH_4,man} = \frac{24 \cdot V_{s,d} \cdot b_1}{1000} \cdot \exp \left[\ln(A) - \frac{E}{RT} \right] + \frac{24 \cdot V_{s,nd} \cdot b_2}{1000} \cdot \exp \left[\ln(A) - \frac{E}{RT} \right] \quad (4)$$

where $E_{CH_4,man}$ is the emission of CH₄ from the storage (kg CH₄ day⁻¹), $V_{s,d}$ and $V_{s,nd}$ are the degradable and nondegradable VS in the manure (g), b_1 and b_2 are rate correcting factors (dimensionless), A is the Arrhenius parameter (g CH₄ kg⁻¹ VS h⁻¹), E is the apparent activation energy (J mol⁻¹), R is the gas constant (J K⁻¹ mol⁻¹), and T is the temperature (K) (table 2).

From Sommer et al. (2004), the degradable volatile solids entering storage is:

$$V_{s,d} = V_{s,tot} \frac{B_o}{E_{CH_4,pot}} \quad (5)$$

where $V_{s,tot}$ is the total VS in the manure (g), B_o is the achievable emission of CH₄ during anaerobic digestion (g kg⁻¹ VS), and $E_{CH_4,pot}$ is the potential CH₄ yield of the manure (g kg⁻¹ VS), which can be estimated using Bushwell's equation and the carbohydrate, fat, and protein content of the manure. For cattle slurry, Sommer et al. (2004) defined B_o as 0.2 g CH₄ kg⁻¹ VS and $E_{CH_4,pot}$ as 0.48 g CH₄ kg⁻¹ VS.

Total VS in the manure storage at any point in time is the difference between that entering the storage and that lost from the storage up to that point. The amount entering can be

Table 2. Parameters and values for the manure storage emissions model of Sommer et al. (2004).

Parameter	Variable	Value	Units
Volatile solids content ^[a]	P_{VS}	0.87, 0.86, 0.84	g VS g ⁻¹ TS
Achievable CH ₄ ^[b]	B_o	0.2	g CH ₄ g ⁻¹ VS
Potential CH ₄ ^[b]	$E_{CH_4,pot}$	0.48	g CH ₄ g ⁻¹ VS
Correcting factors ^[b]	b_1, b_2	1.0, 0.01	dimensionless
Arrhenius parameter ^[b]	$\ln(A)$	43.33	g CH ₄ kg ⁻¹ VS h ⁻¹
Activation energy ^[b]	E	112,700	J mol ⁻¹
Gas constant ^[b]	R	8.314	J K ⁻¹ mol ⁻¹

^[a] Values for heifers, dry cows, and lactating cows from ASABE Standards (2008).

^[b] From Sommer et al. (2004).

determined from the manure mass, the total solids content, and the VS content:

$$V_{s,tot} = M_{manure} \cdot P_{TS} \cdot P_{VS} - V_{s,loss} \quad (6)$$

where M_{manure} is the accumulated mass of manure entering the storage (kg), P_{TS} is the total solids content in the manure (g TS kg⁻¹ manure), P_{VS} is the fraction of VS in the total solids (g VS g⁻¹ TS), and $V_{s,loss}$ is the accumulated VS loss. To obtain a similar rate of VS loss as that reported by Sommer et al. (2004), daily VS loss is predicted as three times the CH₄ loss ($E_{CH4,man}$) from the stored manure. The mass of nondegradable volatile solids, $V_{s,nd}$, is then calculated using a mass balance:

$$V_{s,nd} = V_{s,tot} - V_{s,d} \quad (7)$$

The inputs required for this model are the mass and temperature of the manure in storage. The amount of manure in storage is modeled as the accumulation of that produced by the herd, with daily manure excretion determined in the animal component of IFSM (Rotz et al., 1999). The temperature of the manure in storage on a given simulated day is estimated as the average ambient air temperature over the previous ten days, where daily air temperature is also available in IFSM.

The relationships described above are generally applicable to uncovered slurry storages. Some dairy farms use control technology such as storage covers to reduce emissions. One such technology includes the capture and combustion of the CH₄ gas. This method drastically decreases the emission of CH₄, although it also increases the emission of CO₂ through the combustion of CH₄. To simulate this storage treatment, the emission of CH₄ from an enclosed manure storage is calculated as:

$$E_{CH4,cov} = E_{CH4,man} \cdot (1 - \eta_{eff}) \quad (8)$$

where $E_{CH4,cov}$ is the CH₄ emitted from the enclosed manure storage (kg CH₄ day⁻¹), $E_{CH4,man}$ is the calculated emission of CH₄ from an open manure storage using equation 4 (kg CH₄ day⁻¹), and η_{eff} is the efficiency of the collector (fraction). The efficiency of the collector and flare is assumed to be 0.99 (EPA, 1999). The subsequent flaring of the captured CH₄ releases CO₂, which adds to the overall farm emission of this gas (Chianese et al., 2009a). The additional emission of CO₂ due to the combustion of CH₄ is calculated as:

$$E_{CO2,flare} = E_{CH4,cov} \cdot 2.75 \quad (9)$$

where $E_{CO2,flare}$ is the emission of CO₂ due to combustion of the CH₄ captured from the manure storage (kg CO₂ day⁻¹), and 2.75 is the ratio of the molecular weights of CO₂ and CH₄.

FIELD-APPLIED MANURE

Research has shown that field-applied slurry is a source of CH₄ emissions for several days after application, emitting between 40 to 90 g CH₄ ha⁻¹ day⁻¹ (Sommer et al., 1996; Chadwick and Pain, 1997; Sherlock et al., 2002). Emissions drastically decrease within the first few days, and the soils return to being a neutral source of CH₄ by 11 days (Sherlock et al., 2002).

Sherlock et al. (2002) related CH₄ emissions from field-applied slurry to the volatile fatty acids (VFAs) concentration

in the soil. Because the VFAs in the soil were due to the application of the slurry (Sherlock et al., 2002), their model was used to relate CH₄ emissions to the VFA concentration in the slurry. Therefore, emission of CH₄ from field-applied slurry is predicted as:

$$E_{CH4,app} = (0.170 \cdot F_{VFA} + 0.026) \cdot A_{crop} \cdot 0.032 \quad (10)$$

where $E_{CH4,app}$ is the emission of CH₄ from field-applied slurry (kg CH₄ day⁻¹), F_{VFA} is the daily concentration of VFAs in the slurry (mmol kg⁻¹ slurry), and A_{crop} is the land area (ha) where the manure is applied.

Sherlock et al. (2002) found that the daily VFA concentration exponentially decreased in the days following the application of manure slurry and approached background levels within approximately four days. Using this information, we derived a relationship predicting the daily concentration of VFA in the field-applied slurry:

$$F_{VFA} = F_{VFA,init} \cdot e^{-0.6939 \cdot t} \quad (11)$$

where F_{VFA} is the daily concentration of VFAs in the slurry (mmol kg⁻¹ slurry), $F_{VFA,init}$ is the initial concentration of VFAs in the slurry at the time of application (mmol kg⁻¹ slurry), and t is the time since application (days) with $t = 0$ representing the day of application.

Paul and Beauchamp (1989) developed an empirical model relating the pH of manure slurry to VFA and total ammoniacal N (TAN) concentrations:

$$pH = 9.43 - 2.02 \cdot \frac{F_{VFA,init}}{F_{TAN}} \quad (12)$$

where pH is the pH of the manure slurry (dimensionless), and F_{TAN} is the concentration of TAN (NH₄⁺ + NH₃) in the slurry (mmol kg⁻¹ slurry). By rearranging equation 12, an equation was obtained for predicting the initial concentration of VFAs based on the pH and TAN content of the manure slurry:

$$F_{VFA,init} = \frac{F_{TAN}}{2.02} (9.43 - pH) \quad (13)$$

To predict emissions from field-applied manure, equation 13 was used to determine an initial VFA concentration, and equation 11 was used to track the VFA concentration through time following application. Using this concentration, an emission rate was determined (eq. 10) until the remaining VFA concentration approached zero.

GRAZING ANIMALS

On farms that incorporate grazing for at least a portion of the year, freshly excreted feces and urine are directly deposited by animals on pastures. Studies have shown that feces are a small source of CH₄ and that emissions from urine are not significantly different from background soil emissions (e.g., Jarvis et al., 1995; Yamulki et al., 1999). Although there is evidence that CH₄ emission rates from freshly deposited feces are influenced by environmental conditions and animal rations (Saggar et al., 2004), quantitative relationships describing these influences have not been developed. Therefore, use of a constant emission factor provided the best available approach of representing this emission source. This approach was further justified in that this emission source was relatively small compared to enteric fermentation and manure storage sources (Holter, 1997). To determine an

Table 3. Published emissions of CH₄ from feces directly deposited by dairy animals on pasture lands (all values in g CH₄ kg⁻¹ feces DM).

Reference	Reported Range	Average
Jarvis et al. (1995)	0.31 - 0.95	0.65
Flessa et al. (1996) ^[a]	--	1.25
Holter (1997)	0.21 - 0.90	0.60
Yamulki et al. (1999)	0.09 - 0.65	0.32
Saggar et al. (2004)	0.91 - 1.03	0.97
Average emission factor		0.76

^[a] Measured over a whole pasture, whereas other publications report emissions from individual fecal deposits.

emission factor, emission rates from five published studies were averaged to obtain a factor of 0.76 g CH₄ kg⁻¹ DM of feces deposited in the pasture (table 3). For grazing systems, the daily emission of CH₄ is predicted as the product of this emission rate and the daily amount of feces DM deposited by grazing animals.

BARN EMISSIONS

Manure on housing facility floors is also a small source of CH₄. No published model or data were found for this emission source. Therefore, unpublished CH₄ emission data measured from free-stall barn floors (E. Wheeler, unpublished data, 2008, The Pennsylvania State University, University Park, Pa.) were used to develop an empirical equation relating CH₄ emission to the air temperature in the barn. The resulting model ($R^2 = 0.49$) is:

$$E_{CH_4, floor} = \max(0.0, 0.13T(A_{barn}) / 1000) \quad (14)$$

where $E_{CH_4, floor}$ is the daily rate of CH₄ emission from the barn floor (kg CH₄ day⁻¹), T is the air temperature (°C), and A_{barn} is the area of the barn floor covered with manure (m²). At temperatures below 0°C, the emission is zero.

As an empirical equation that correlates CH₄ emission with temperature, equation 14 satisfies criteria 3, 4, and 5 of our model requirements. The temperature dependence of CH₄ production is well documented (Zeikus and Winfrey, 1976; van Hulzen et al., 1999). This simple relationship predicts reasonable emission rates for temperatures of 0°C and greater. Because this emission source is a relatively minor contributor to overall farm-level CH₄ emissions, development of a more detailed process model was not justified.

MODEL EVALUATION

Few data exist on overall emissions of CH₄ from dairy farms in the U.S. (Chianese et al., 2009c). Studies that have quantified CH₄ emissions from specific farm sources often have not provided the specific input data required to simulate scenarios in IFSM. In addition, these studies were often small-scale or laboratory studies that could not be adequately simulated in IFSM. Therefore, we evaluated IFSM predictions of CH₄ emissions in three ways. First, for the major emission sources of enteric fermentation and manure storage, observed data from previous studies were compared to simulated emissions. Studies were selected that represented long-term emissions (Chianese et al., 2009c) and that included the major input information required to simulate the observed conditions with IFSM but were not a source of data in the development of the original model. Second, a sensitivity analysis was performed on the important parameters of the major

model components. Finally, IFSM was used to simulate a representative farm in Pennsylvania, and the predicted emissions were compared to those previously identified as typical (Chianese et al., 2009c). Based on this evaluation, the uncertainty in model predictions is discussed.

ENTERIC FERMENTATION EMISSIONS

Studies by Kirchgessner et al. (1991) and Kinsman et al. (1995) were used to evaluate our model's ability to simulate CH₄ emissions from dairy animals. Kirchgessner et al. (1991) summarized CH₄ emissions from seven metabolism trials employing 67 lactating cows with an average weight of 583 kg and an average daily milk production of 17.0 kg cow⁻¹. The animals were fed diets consisting, on average, of 57% roughage composed of grass hay and corn silage with the remainder from various concentrates. They reported an average daily CH₄ emission of 300 g CH₄ cow⁻¹ (± 39 g CH₄ cow⁻¹). For trials with relatively low feed intake (about 12 kg DM cow⁻¹ day⁻¹), the reported average emission was 270 g CH₄ cow⁻¹ day⁻¹, and with a DM intake of 16 kg cow⁻¹ day⁻¹, the average emission was 334 g CH₄ cow⁻¹ day⁻¹.

Although specific experiments could not be simulated, IFSM was used to represent the average diet characteristics, cow weight, and milk production from the reported studies. For the overall average conditions, the predicted emission was 299 g CH₄ cow⁻¹ day⁻¹, very similar to the average of all trials and well within one standard deviation of the mean reported by Kirchgessner et al. (1991). When animal weights and milk production were adjusted to obtain feed intakes of 12 and 16 kg DM cow⁻¹ day⁻¹, predicted daily emissions were 263 and 339 g CH₄ cow⁻¹, respectively. The close similarity between measured and predicted emissions demonstrates that IFSM is capable of predicting CH₄ emissions from enteric fermentation in dairy cattle.

In a longer-term study, Kinsman et al. (1995) measured CH₄ emissions from 118 lactating cows over a 6-month period. Cows weighed an average of 602 kg with an average daily milk production of 28.5 kg cow⁻¹ (± 2.3 kg cow⁻¹). On average, animals were fed 17.5 kg DM cow⁻¹ day⁻¹ (± 1.4 kg DM cow⁻¹ day⁻¹) of mixed forage and concentrate. The diet consisted of corn silage, alfalfa silage, hay, grain, roasted soybean, soybean meal, and other supplements (Kinsman et al., 1995). They reported daily CH₄ emissions from enteric fermentation ranging from 431 to 686 L CH₄ cow⁻¹ with an average rate over the 6-month period of 552 L CH₄ cow⁻¹. Considering a CH₄ density of 0.68 kg m⁻³ at atmospheric pressure and temperatures around 15°C, this range in daily emissions is 293 to 466 g CH₄ cow⁻¹ with an average of 375 g CH₄ cow⁻¹. Using similar diet characteristics and milk production, IFSM predicted an average daily emission of 375 g CH₄ cow⁻¹. This simulated emission was within the range, and equal to the average, of CH₄ emission rates reported by Kinsman et al. (1995), further supporting that IFSM predicts very reasonable CH₄ emissions from enteric fermentation. IFSM was also able to accurately predict CO₂ emissions for this same study (Chianese et al., 2009a).

MANURE STORAGE EMISSIONS

A study by Husted (1994) was used to test the ability of IFSM in predicting CH₄ emissions from slurry manure storages. Husted measured CH₄ emissions from slurry manure obtained from 160 Jersey cows and their calves, which was

stored in a 1,200 m³ outdoor tank in Denmark. Over an annual period, daily CH₄ emissions from the uncovered storage ranged from 5 to 35 g m⁻³ d⁻¹ as slurry temperature varied from 6 °C to 18 °C. From these emission measurements, an annual emission of 15.5 kg animal⁻¹ was estimated, which gave an annual emission from the storage of 2,480 kg CH₄. The confidence limits of the data reflected an uncertainty of 30% in this estimate.

A representative farm was simulated with IFSM using the reported animal, manure, and storage characteristics. The farm was simulated over 25 years of historical weather data from Thisted, Denmark (1974 to 1998). Over manure slurry temperatures of 6 °C to 18 °C, simulated CH₄ emissions were 3.8 to 27 g CH₄ m⁻³ d⁻¹, which was similar to the range in measured values. Simulated average annual emissions ranged from 2,150 to 3,500 kg CH₄ with a 25-year average of 2,765 kg CH₄. These annual values were within the uncertainty of Husted's estimated value, and the 25-year average emission was within 12% of his estimated annual emission. This comparison of simulated and measured emissions supports that the model predicts very reasonable emissions from stored cattle slurry manure.

SENSITIVITY ANALYSIS

Models are more sensitive to some parameters and inputs than others; it is therefore important to quantify this sensitivity to ensure that values of variables with the most impact are accurate. A sensitivity analysis was performed on the modules developed for enteric fermentation, manure storage, and field-applied manure. For this analysis, each selected parameter was varied by a set percentage, and the percent change in the output was determined. To perform this analysis, the CH₄ relationships were developed into an ad-hoc program using Matlab. Modifications to the CH₄ relationships were made as necessary to achieve mathematically correct and physically realistic output while maintaining the scientific validity of the equations. Because a function was created for each emission source, the inputs and parameters were easily changed and the relevant outputs obtained. This method allowed the sensitivity of important parameters (table 4) to be quantified while maintaining the interaction among variables. Data generated by changing the value of each parameter by $\pm 25\%$ were used to calculate a sensitivity index:

$$SI = \left(\frac{y_{+ \%} - y_{- \%}}{x_{+ \%} - x_{- \%}} \right) \left(\frac{x_{base}}{y_{base}} \right) \quad (15)$$

where *SI* is the sensitivity index (dimensionless), and *x_{base}* is the model parameter used to obtain the output *y_{base}*. A value of one indicates that a 25% change in *y* occurs with a 25% change in *x*; a lesser ratio indicates lesser sensitivity, whereas a greater ratio indicates greater sensitivity.

The enteric fermentation output was not highly sensitive to any of the model parameters. For a given percent change in the input, all of the parameters caused the same, or less, change in CH₄ emissions. The most important parameter was the maximum possible CH₄ emission; the predicted emission rate was proportional to this assigned value (table 4).

For the manure storage module, the majority of parameters had sensitivity values of 1.0. In other words, a given change in the input parameter caused the same change in the output (table 4). However, the model was very sensitive to the Arrhenius parameter, which had a sensitivity greater than

Table 4. Sensitivity analysis for the CH₄ module.

	Variable ^[a]	Change in input (%)	Sensitivity index ^[b]
Enteric fermentation	<i>MEI</i>	25	0.7
	<i>E_{max}</i>	25	1.0
	<i>R_{diet}</i>	25	0.2
	<i>c</i>	25	0.7
Manure storage	<i>P_{ts}, P_{vs}</i>	25	1.0
	<i>B_o</i>	25	0.98
	<i>E_{CH4,pot}</i>	25	1.04 ^[c]
	<i>b₁, b₂</i>	25	0.99
	<i>ln(A)</i>	25	>>100 ^[d]
	<i>M_{man}</i>	25	1.0
	<i>T_{10C}</i>	25	1.7
	<i>T_{25C}</i>	25	4.3
Field application	<i>F_{TAN}</i>	25	0.99
	<i>M_{man}</i>	25	0.01
	<i>pH</i>	25	5.6
	<i>t</i>	25	0.7 ^[e]
	<i>R_{app}</i>	25	1.1 ^[f]

- [a] *P_{ts}, P_{vs}* = total solids and volatile solids (VS) concentrations (%)
B_o = achievable CH₄ yield (g CH₄ kg⁻¹ VS)
E_{CH4,pot} = maximum potential CH₄ yield (g CH₄ kg⁻¹ VS)
b₁, b₂ = rate correction factors for degradable and nondegradable VS (dimensionless)
ln(A) = Arrhenius parameter (g CH₄ kg⁻¹ VS h⁻¹)
M_{man} = mass of manure (kg)
T_{10C}, T_{25C} = temperature (°C)
F_{TAN} = total ammoniacal nitrogen in manure (mmol kg⁻¹ slurry)
pH = pH of the slurry (dimensionless)
t = time until incorporation (days)
R_{app} = manure application rate (kg m⁻²)
MEI = metabolizable energy intake (MJ animal⁻¹)
E_{max} = maximum possible emission of CH₄ (MJ animal⁻¹ d⁻¹)
R_{diet} = ratio of starch to ADF in diet (g g⁻¹)
c = shape parameter to calculate enteric fermentation.
[b] The sensitivity index is the ratio of the change in output over the change in input. For example, if change = 1.0, then a 25% change in input yielded a 25% change in output.
[c] Varying *E_{CH4,pot}* by 10% and 50% yielded 1.0 and 1.3, respectively.
[d] The model was very sensitive to changes in the Arrhenius parameter with a change much greater than 100.
[e] Varying *t* by 10% and 50% yielded 1.7 and 0.5, respectively.
[f] Varying *R_{app}* by 10% and 50% yielded 1.0 and 1.3, respectively.

100. The Arrhenius parameter accounts for the temperature dependency of CH₄ emissions from manure storage. This parameter is an established constant within the model that should not be changed. An appropriate value for the Arrhenius parameter was determined by the original developers of the manure storage model by fitting the parameter to observed data. The value selected ensured that annual CH₄ emissions from slurry storage corresponded to emissions calculated using IPCC emission factors (Sommer et al., 2004). As a result, the present Arrhenius parameter provides the best available model. Additional studies quantifying CH₄ emissions from slurry storage are required to further evaluate and perhaps improve the determination of this parameter (Sommer et al., 2004).

As with the manure storage model, most parameters in the field-applied manure module caused approximately the same percent change in output as the change in input. The pH of the manure slurry was the only variable that caused a major difference in the output, as evidenced by a five-fold change in output for a given change in input. Currently, the pH of slurry at the time of field application is held constant in IFSM at a value of 8.0; future work may improve the prediction of CH₄

emissions by developing a model to predict changes in slurry pH. However, as illustrated in the following section, this emission source is very small compared to other farm sources, so a more detailed model was not warranted at this time.

The majority of CH₄ emissions from the farm were due to enteric fermentation. Even though the manure storage and field application modules were very sensitive to certain parameters, the impact of this sensitivity on farm emissions was small relative to that of enteric fermentation. A 25% change in the enteric fermentation, manure storage, and field application emissions of CH₄ caused about a 15%, 2% and negligible change in the net GHG emission of the farm, respectively. Thus, changes to parameters in the manure storage and field application modules had a relatively small impact on net farm GHG emissions, even though some parameters were highly sensitive.

REPRESENTATIVE FARM EMISSIONS

As a final evaluation, simulated annual whole-farm emissions were compared to those previously summarized from prior literature for a hypothetical dairy farm in central Pennsylvania (Chianese et al., 2009c). Only a brief description of the farm is provided to document those assumptions most relevant to CH₄ production and emission. This representative farm included 85 lactating Holstein cows (average mass of 650 kg), 15 non-lactating cows (average mass of 700 kg), 38 heifers over one year in age (average mass of 470 kg), and 42 heifers under one year in age (average mass of 200 kg). Animals were housed in free-stall barns where they were fed total mixed rations consisting of corn, alfalfa and grass silages, high-moisture corn, and purchased supplemental feeds as required to meet animal nutrient needs. Manure was scraped daily, stored in a 3,000 m³ storage tank for up to six months, and applied to cropland in the spring and fall. On average over the full year, the storage contained about 1,100 m³ of manure. The 90 ha farm area consisted of 20 ha of grass, 20 ha of alfalfa, and 50 ha of corn. Most of the crop nutrient requirements were met through manure nutrients generated on the farm, but N fertilizer was applied at rates of 50 and 70 kg ha⁻¹ on corn and grassland, respectively.

Based on the above farm characteristics, IFSM was used to simulate this representative farm in central Pennsylvania

using historical State College weather (1982 to 2006). The simulated annual emission from animals and housing facilities was 14,202 kg CH₄, primarily from enteric fermentation with a small emission from barn floors (table 5). Other emissions included 6,971 kg CH₄ from the manure storage and 20 kg CH₄ following field application of manure (table 5). This gave a total annual emission of 21,193 kg CH₄ from this representative dairy farm. For the overall farm, this predicted emission was very similar to the rate of 22,931 kg CH₄ year⁻¹ that was previously estimated as a typical emission for a dairy farm of this size, based on a review of published emission data (table 5). The major difference between the simulated and previously estimated data was the emission of lactating cows. As illustrated in the next section, this emission is sensitive to the amount of forage in their diet. This simulation used a minimum amount of forage in lactating cow diets, and a relatively small increase in the amount of forage fed can easily explain this difference in CH₄ emission. Overall, this comparison verifies that IFSM can simulate farm-level CH₄ emissions very similar to those summarized from previous studies.

MODEL UNCERTAINTY

Any farm-level estimation of GHG emissions will have uncertainty associated with the prediction. It is not possible to make a long-term measurement of net farm GHG emission, and even if it were done, that too would have uncertainty. To determine the uncertainty in a net farm emission, uncertainties of each of the components must be defined. Statistical quantification of the uncertainty of components of a biological system requires large data sets. Since adequate data are not available, the IPCC (2006a) has chosen to use expert opinion to estimate the uncertainty of their emission factors in predicting GHG emissions. They estimate that their Tier 2 methodologies provide emission factors for CH₄ from enteric fermentation and manure handling with uncertainties of $\pm 20\%$ (IPCC, 2006b). This is the uncertainty associated with general application of their emission factors. Creating and applying their Tier 2 emission factors to well defined conditions can reduce this uncertainty (IPCC, 2006a).

The uncertainty estimations of the IPCC provide the best information available for quantifying the uncertainty of predicting farm GHG emissions. Based on our experience in

Table 5. Comparison of previously estimated (Chianese et al, 2009c) and model-predicted annual CH₄ emissions from a representative dairy farm in Pennsylvania.

		Representative Farm Analysis			IFSM Simulated Emission (kg CH ₄)
		Emission Factor ^[a]	Farm Parameter	Emission (kg CH ₄)	
Animals and housing	Lactating cows	106 kg CH ₄ LU ⁻¹	111 LU ^[b]	11,766	7,312 ^[c]
	Dry cows	58 kg CH ₄ LU ⁻¹	20 LU	1,160	1,556
	Replacement heifers	77 kg CH ₄ LU ⁻¹	52 LU	4,000	4,950
	Barn floors	--	--	--	384
Manure storage		5.6 kg CH ₄ m ⁻³	1100 m ³	6,160	6,971
Croplands	Grass	-1.4 kg CH ₄ ha ⁻¹ year ⁻¹	20 ha	-28	--
	Alfalfa	-2.6 kg CH ₄ ha ⁻¹ year ⁻¹	20 ha	-52	--
	Corn	-1.5 kg CH ₄ ha ⁻¹ year ⁻¹	50 ha	-75	--
Field application		--	--	--	20
Total				22,931	21,193

^[a] Emission factors were obtained from Chianese et al., 2009c.

^[b] LU = livestock unit of 500 kg body mass.

^[c] This emission was relatively low compared to the representative farm because the simulated farm used a minimum forage diet for lactating animals, whereas the experimental data supporting the representative farm analysis typically reflects greater use of forage in these diets.

evaluating our model, we believe that the uncertainty in predicting CH₄ emissions during manure storage and handling is well represented by the $\pm 20\%$ suggested by the IPCC (2006b). For predicting emissions from enteric fermentation for specific animals on well defined diets, the model is more accurate. For this component, we suggest an uncertainty of $\pm 10\%$. The uncertainties of all farm components can be combined, in which the overall uncertainty is the square root of the sum of the squares of the emission of each component times its uncertainty (IPCC, 2006a). Using this procedure, the uncertainty in estimating the total CH₄ emission from enteric fermentation, manure storage, and manure application in the field is $\pm 9\%$. Including the uncertainties in predicting CO₂ (Chianese et al., 2009a) and N₂O (Chianese et al., 2009b) emissions, the uncertainty in the estimated net farm GHG emission is $\pm 13\%$, with about half of this uncertainty due to that in predicting CH₄ emissions.

MODEL APPLICATION

Four whole-farm simulations were done to illustrate the use of the model in evaluating management impacts on CH₄ emissions from dairy farms. Important factors that effect CH₄ production include animal diets and management of stored manure. The model was used to simulate the 100-cow representative dairy farm described above, and then management changes were made to simulate the use of higher-forage diets, the use of grazing along with higher-forage diets, and the use of a covered manure storage with a flare to burn the biogas produced.

For the base farm, lactating cows were fed a relatively high-grain diet (table 6, column 1). This has been a common practice in the past, with relatively inexpensive grain for feed supplementation. With a recent increase in grain prices, there is incentive to feed more forage produced on the farm with less grain supplementation. This management change was simulated by switching the diet formulation for the lactating

herd from minimum forage to a maximum forage ration (Rotz et al., 1999). To obtain the additional forage needed, more of the corn produced on the farm was harvested as corn silage with less harvested as high-moisture grain. This produced 115 Mg DM more forage and 49 Mg DM less grain for feeding the herd (table 6, column 2 vs. 1). Total feed intake was increased about 2%, with an annual average of 44 Mg DM less supplemental feed purchased and brought onto the farm. With the higher-forage diets, animals produced about 21% more CH₄ through enteric fermentation. This also increased the VS content in the stored manure, which increased the emission from the storage by 6%.

This change also impacts the other GHG emissions of N₂O (Chianese et al., 2009b) and CO₂ (Chianese et al., 2009a). Although the details of these processes are not presented here, the simulation indicates a small decrease in N₂O emission with greater use of corn silage. This occurs because more N is being removed in the corn silage and recycled through the animals as compared to grain harvest and feeding. Carbon dioxide emission is also reduced with greater use of corn silage. With grain harvest, greater amounts of stover are left in the field, which creates greater microbial decomposition and ultimately more CO₂ emission through microbial respiration. By removing the whole plant in corn silage harvest, less crop residue is left in the soil to enhance microbial respiration. Overall, this management change had little effect on the total global warming potential of the GHGs emitted from the farm (table 6, column 2 vs. 1).

When the use of higher-forage diets was combined with grazing, some net reduction in GHG emission was obtained (table 6, column 3 vs. 2). For this strategy, all of the 20 ha of grass was rotationally grazed from late April through October by the older heifers and all cows. All other farm parameters, including milk production, were set the same as the previous scenario. With the use of grazing, harvested forage production was reduced 22%. A little more grain was produced, and purchased feed was reduced 19%. Enteric methane production increased 2% with the use of pasture forage, but with

Table 6. Annual production and greenhouse gas emissions of three production strategies on a simulated representative dairy farm in central Pennsylvania.^[a]

	Base Farm, Low-Forage Diet ^[b]	High-Forage Diet ^[c]	High-Forage Diet with Grazing	Low-Forage Diet with Enclosed Manure Storage ^[d]
Feed production and use (Mg DM)				
Harvested forage	522	637	494	518
Grazed forage	0	0	147	0
Harvested grain	161	112	123	163
Purchased feed	201	157	127	203
Total feed intake	884	906	891	884
Greenhouse gas emissions (kg)				
Methane	21,193	24,508	19,454	14,287
Animal and barn floor	14,203	17,102	17,458	14,195
Manure storage	6,971	7,387	1,986	70
Field application	20	19	11	22
Nitrous oxide	642	628	681	454
Carbon dioxide	150,478	79,249	38,780	172,611
Net farm emission (CO ₂ e) ^[e]	871,619	879,093	728,068	665,078

^[a] 100 Holstein cows producing 9,000 kg per cow of milk plus 80 replacement heifers housed year round in free-stall barns with feed produced from 50 ha of corn, 20 ha of perennial grassland, and 20 ha of alfalfa.

^[b] Lactating herd fed a maximum-forage diet (60% of forage from corn silage) while maintaining 9,000 kg cow⁻¹ milk production.

^[c] Lactating herd fed a minimum-forage diet (50% of forage from corn silage) while maintaining adequate fiber for 9,000 kg cow⁻¹ milk production.

^[d] Farm with low-forage diet and enclosed manure storage. Methane from storage is converted to CO₂ through combustion (99% efficiency).

^[e] Total CO₂-equivalent greenhouse gas emission considering the global warming potential of CH₄ and N₂O to be 25 and 298 times that of CO₂, respectively.

much less manure being stored during the summer months, CH₄ emissions from manure storage and field application were greatly reduced. With these changes, total CH₄ emission from the farm was reduced 21% compared to the high-forage feeding strategy without grazing. Nitrous oxide emission increased 8% due to the higher concentration of N in urine deposits (Chianese et al., 2009b), and net CO₂ emission decreased through greater use of farm-produced feeds (Chianese et al., 2009a). Overall, net GHG emission was reduced 17% with the use of this grazing strategy.

With an enclosed manure storage, the CH₄ produced can be captured and burned. Combustion of the biogas transforms the CH₄ to CO₂ (Chianese et al., 2009a). Since CO₂ has 25 times less global warming potential, the net result is a reduction in GHG emissions. Compared to the open storage tank in the low-forage diet scenario, simulated CH₄ emission from the storage was reduced by 99% while net farm CO₂ emission was increased 15% (table 6, column 4 vs. 1). Methane emission following field application was increased a small and unimportant amount. Covering the manure storage also eliminated N₂O emission from the storage by preventing crusting on the manure surface (Chianese et al., 2009b). The overall net effect of using this strategy was a 24% reduction in the total global warming potential of the whole-farm emission of GHGs (table 6, column 4 vs. 1).

CONCLUSIONS

A module simulating CH₄ emissions from enteric fermentation, slurry manure storage, field-applied manure, feces deposited in pasture, and manure on free-stall barn floors was developed from previously published relationships and experimental data and added to a farm simulation model (Integrated Farm System Model, or IFSM). Relationships selected were consistent with our modeling objectives and the current structure of IFSM.

The expanded IFSM was shown to predict CH₄ emissions that were consistent with reported emissions from specific experiments and data summarized for whole dairy farm systems. A sensitivity analysis identified important parameters and illustrated that model predictions responded appropriately to changes in model parameters.

Incorporation of the CH₄ module with IFSM, along with modules simulating CO₂ and N₂O emissions, provides a tool for evaluating the overall impact of management scenarios used to reduce GHG emissions from dairy farms. Farm simulations showed that increasing the use of forage (corn silage) in animal diets increased CH₄ emission by 16% with little impact on the global warming potential of net farm emissions of all GHGs. Use of grazing along with high-forage diets reduced CH₄ and net farm GHG emissions by 8% and 16%, respectively. Using a manure storage cover and burning the captured biogas reduced farm emission of CH₄ by 32% with a 24% reduction in the net farm emission of GHGs.

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